EVALUATION OF PANORAMIC RECONNAISANCE AERIAL PHOTOGRAPHY FOR MEASURING ANNUAL MORTALITY OF LODGEPOLE PINE CAUSED BY THE MOUNTAIN PINE BEETLE

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ABSTRACT

High elevation, panoramic infrared photography taken from a U-2 aircraft was evaluated to determine its effectiveness in quantifying annual mortality of lodgepole pine caused by the mountain pine bettle in a 520,640-acre outbreak in portions of the Beaverhead and Gallatin National Forests in Montana. A multistage, variable probability design using probability proportional to size (PPS) at three levels was used throughout the survey.

The results suggest that panoramic photography can be effectively used to provide precise estimates of mountain pine beetle-caused annual mortality of lodgepole pine over large areas. Mortality of lodgepole pine in 1977 was estimated at 1,891,510 ± 194,804 trees, and 27,001 M ± 3682 M cubic feet of volume. These estimates differed somewhat from a multistage aerial photo survey also conducted in 1978, the difference ascribed to different areas of coverage. Physical characteristics of this unconventional format are described, and suggestions for its future use in similar bark beetle damage surveys are recommended.

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EVALUATION OF PANORAMIC RECONNAISSANCE AERIAL PHOTOGRAPHY FOR MEASURING ANNUAL MORTALITY OF LODGEPOLE PINE CAUSED BY THE MOUNTAIN PINE BEETLE [1-3]. p.3

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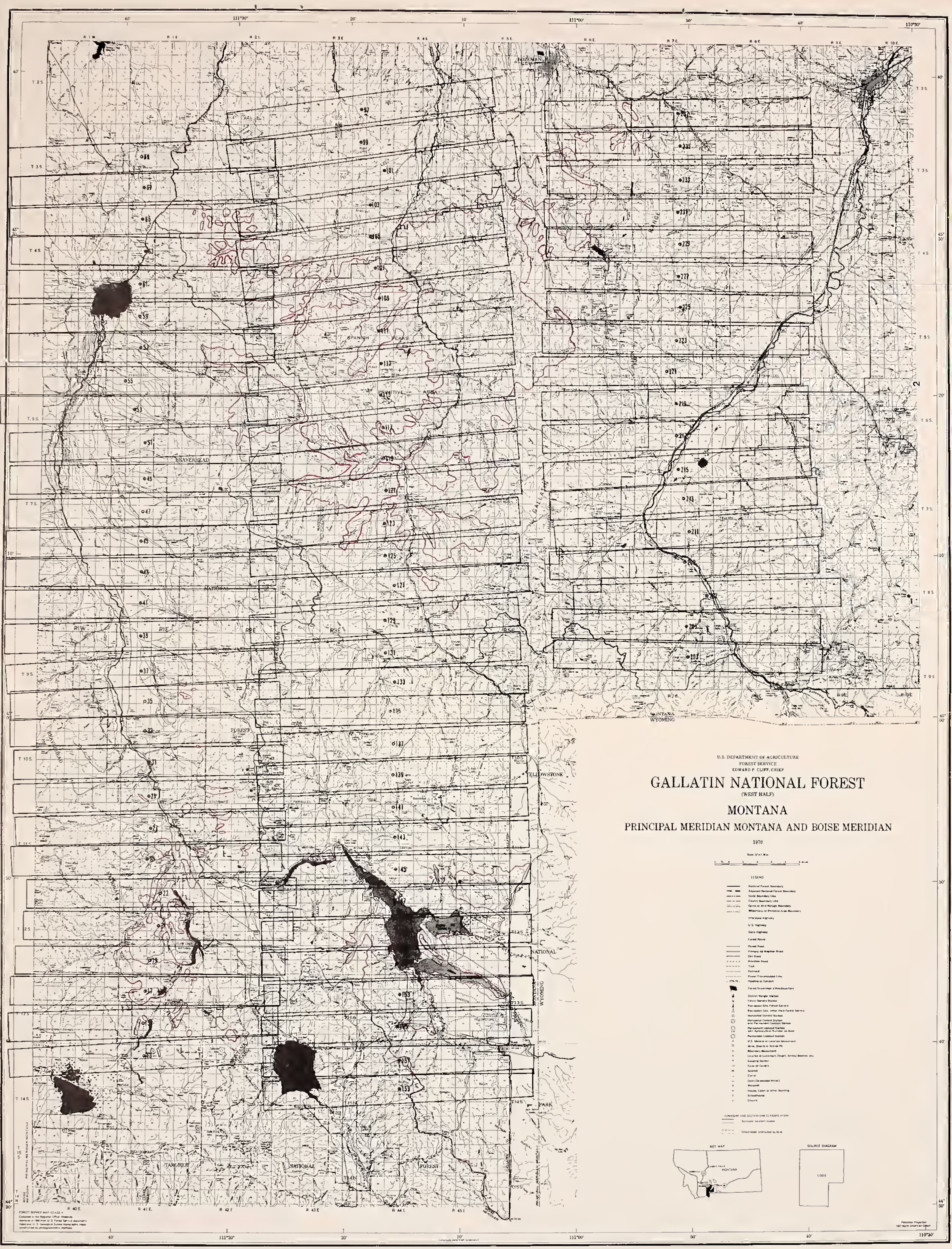


1. *Portions of the Beaverhead and Gallatin National Forests showing the location of the OB frames (±40°) and distribution of the mountain pine beetle (in red) as determined during a 1978 aerial sketchmap survey. Nadir is shown as a circle to the left of the frame numbers.*

INTRODUCTION

Sound data on tree damage and mortality caused by destructive forest insects and diseases is required for pest management decision making at all planning levels. During the past two years, Forest Insect and Disease Management has conducted multistage surveys to estimate annual mortality of lodgepole (*Pinus contorta* var. *latifolia* Engelm.) and ponderosa pine (*Pinus ponderosa* Laws) caused by the mountain pine beetle (*Dendroctonus ponderosa* Hopkins). These surveys, conducted in portions of the Targhee National Forest, Idaho, and the Black Hills National Forest, South Dakota and Wyoming, have provided precise estimates of mountain pine bettle-caused tree mortality over large areas with reasonable sampling errors (Klein *et al.* 1979, Hostetler and Young 1979a,b). Flexibility of the general survey design allows for application to small areas as well as large areas, e.g., a National Forest.

Medium-scale, reconnaissance photography in a panoramic format taken from high altitudes (65,000 feet) has recently been made available for resource management applications. This photography has an advantage over conventional aerial photography in that large areas can be photographed in a relatively short period of time. The panoramic film can then be used for preliminary classification as well as direct sampling, thus eliminating need for aerial sketchmap surveys. The photography is acquired by the Itek KA80A optical bar (OB) camera, and has been used to estimate volumes of dead timber on the Clearwater National Forest, Idaho (Duggan *et al.* 1977), and to stratify and quantify insect-killed trees in California (Klein *et. al.* 1978).

OBJECTIVE

Objective of this survey was to evaluate the capabilities of KA80A OB color infrared photography for measuring annual mortality of lodgepole pine caused by the mountain pine beetle. In addition, an attempt was made to produce an accurate map showing the distribution and relative intensity of tree mortality. These maps could be integrated with a geographic data base and serve as a management tool.

DESCRIPTION OF TEST SITE

The test site was in portions of the Gallatin and Beaverhead National Forests in south central Montana (figure 1). The area is comprised of parts of the Madison and Gallatin Mountain ranges, separated by the Gallatin River, and lying between the Yellowstone and Madison Rivers. Elevations range from slightly over 5000 feet in the Gallatin River Valley to more than 11,000 feet in the Madison Range. The generally steep terrain consists of U-shaped glacial valleys, sharp ridges, almost vertical headwalls, and treeless peaks. The dominant conifer is lodgepole pine, with lesser amounts of Douglas-fir [*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco], Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), subalpine fir [*Abies lasiocarpa* (Hook.) Nutt.], whitebark-limber pine (*Pinus* spp.), and ponderosa pine.

The present mountain pine beetle outbreak began in the late 1960's. These infestations occur in portions of the Gallatin and Hebgen Lake Ranger Districts of the Gallatin National Forest, and in the Jack Creek and West Fork drainages of the Madison River on the Beaverhead National Forest. During 1978, upwards of 60 trees per acre were killed in the Hebgen Lake Ranger District (McGregor *et al.* 1978). In many locales the beetle has moved into higher elevations and is attacking whitebark and limber pines.

CHARACTERISTICS OF PANORAMIC PHOTOGRAPHY

A single panoramic frame, produced by a 120° sweep of the KA80A Itek camera, measures 4.5 × 50 inches and covers an area of approximately 2.6 miles (intrack at nadir) by 43 miles (crosstrack). The scale at nadir is approximately 1:30,000[2] assuming average terrain elevations of 5000 feet. The scale decreases outward from nadir and reaches a minimum of 1:60,000, because of the panoramic angle. Due to the decreasing scale, increasing image obliquity, and color attenuation problems near the film edge, the effective working angle was judged to be 80° or ± 40° from nadir. These characteristics are unique to panoramic photography, and though present in metric frame camera systems, they generally are not as severe. Additionally, panoramic photography presents geometric problems that result from panoramic and topographic distortions, and from variations in aircraft attitude. Panoramic distortion in this survey was removed by use of equal-area grid overlays (nadir scale 1:30,000). Panoramic distortion as well as other errors can be removed by map-registered grid overlays which permit relatively accurate transfer of data from photo to maps. The systems that provide both of these computer-generated grids were developed by the Forest Service WO Geometronics Development Group[3]. Map-registered grids, although more accurate, require more effort to produce, and are considerably more expensive than equal-area grids.

2 The scale at sea level is 1:32,500.

3 Liston. R.L. 1978. Grid generation cost and production rate analysis for the Northern California Test Project. Multilithed. 15 pp.

METHODS

Survey Design in Brief

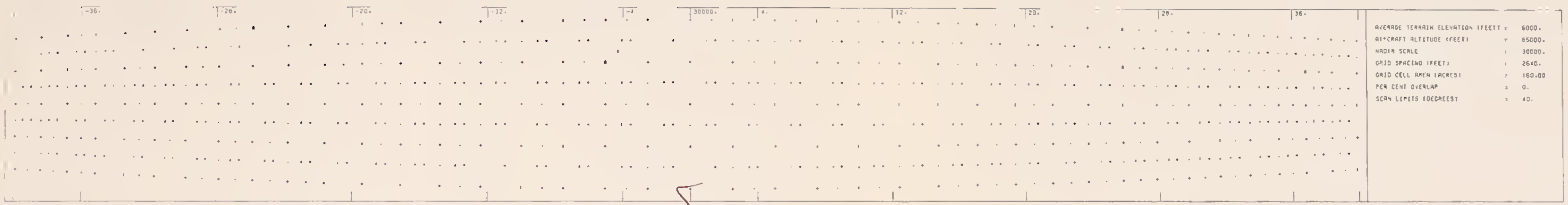
A multistage, variable probability design was used for this survey. A total of 79 alternate panoramic frames encompassing the infestation were obtained during the photo mission. These were divided into 160-acre squares using equal-area transparent grids (figure 2). Experienced aerial photo interpreters using specially adapted microfiche viewers made quick estimates of the number of faders within each 160-acre plot. This first cut produced a list from which 120 160-acre plots were selected for detailed photo interpretation by probability proportional to size (PPS). These plots were then further divided into sixteen 10-acre squares using a second series of equal-area grids. All faders[4] within each 10-acre plot were then counted in stereo. From this second list, thirty 10-acre plots were then selected by PPS for ground truth. However, only 20 plots were actually examined because of time and personnel constraints. Ground crews, viewing the photography in stereo, located the plots, established plot boundaries, and systematically recorded all faders.

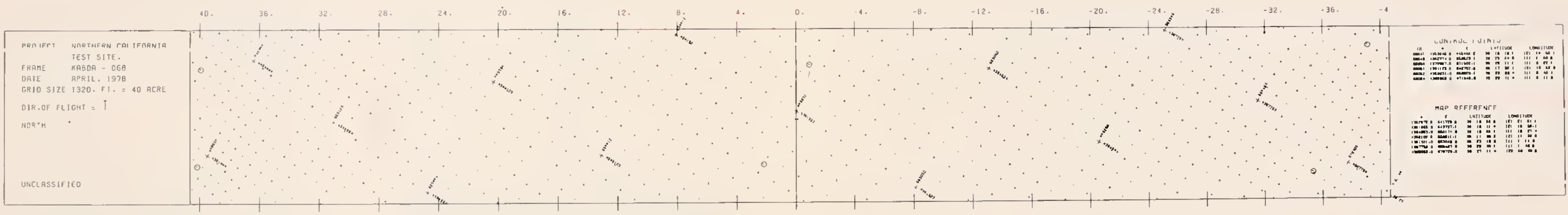
Aerial Photography

Photography was taken July 25, between 12:12 and 12:59 pm MDT (47 minutes), by a U-2 aircraft flying from Moffett Field, California. The aircraft flew at 19,800 M (65,000 feet) at 400 nm (460 miles) per hour. The aircraft was to fly three parallel flight lines at an interval of 17 nm (19.6 miles). High definition Aerochrome infrared reconnaissance film (SO-131) was taken with the KA80A Itek OB camera. Two hundred and fifty-one frames were taken in the stereo mode. Theoretically, the outbreak should have been covered with 79 alternate (nonstereo) frames, but due to aircraft alignment problems and the inherent voids between adjacent equal-area grids, complete coverage was not achieved. The target area was cloud-free and the quality of photography was judged excellent by NASA standards[5].

4 A fader is a mountain pine beetle-killed lodgepole pine whose crown discolors the season (1978) following attack (1977). An (old) fader is a tree attacked and killed the previous year (1976).

5 Flight Summary Report 1165. NASA Ames Research Center, Moffett Field, CA, July 25, 1978. 4 pp.



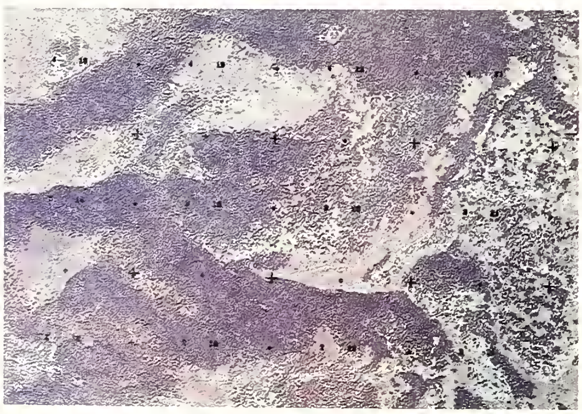


2. *Grid overlays of 1:30,000 scale (at nadir) used with OB panoramic photography.*
Top: *Equal-area grid used in this survey.*
Bottom: *Map-registered grid used in the Northern California study (Klein* et al. *1978). This flight was flown on a diagonal course, which is not recommended.*

During an earlier study in which OB and frame camera systems were compared, the color quality of the OB imagery was judged to be relatively unsatisfactory (Klein *et al.* 1978). On August 8, 1978, prior to the first film duplication run, selective color filters were used to enhance the appearance of the faded tree crowns (#10 red) and to subdue the normal cyan overtone (#20 yellow). This process improved the overall color balance but may have resulted in a slight degradation of spatial resolution. The overall quality of the imagery still was judged excellent.

Indexing the Photography

The panoramic photography was obtained from Moffett Field on September 17, 1979. Prior to the initial classification process, 1:30,000 scale equal-area transparent overlays were temporarily attached to the emulsion (top) side of those alternate frames that covered the infestation (figures 2, 3). In order to locate each frame on the map (figure 1), it was necessary to construct a second transparent grid at map scale, i.e., 1:126,720 (1 inch = 2 miles). Nadir of each frame was then located and transferred to the map. Two crosstrack points that could be identified on both the photography and the map were then transferred to the map. These conjugate points were then located on the large grid, transferred to the small grid, and then matched to their conjugate points on the map. In the event the points did not match (due to elevational displacement) they were equally apportioned on the map.



3. Portion of OB frame near nadir overlaid with transparent equal-area grid (35mm Kodachrome enlargement).

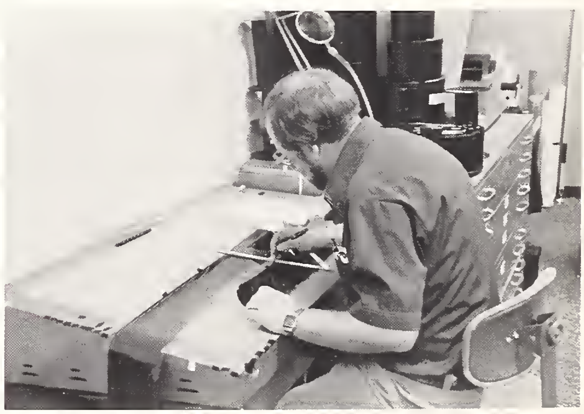
Classification

First step in the initial classification process was to minimize the actual photointerpretation by scanning frames over a conventional light table and eliminating all cells not requiring examination, including areas of non-forest or non-host type, and those duplicated in the endlap regions (figures 4, 5). Interpreters were then able to concentrate only on those cells having lodgepole pine and a likelihood of infestation. Although all six photointerpreters were experienced, none had prior experience interpreting color infrared photos of lodgepole pine killed by the mountain pine beetle, and only three had prior experience with panoramic photography.

The imagery was viewed under 9x to 12x magnification[6] with specially adapted microfiche viewers (figure 6). Quick estimates of the number of faders were made in each cell having lodgepole pine-type and entered on a standard form (figure 4). Cells estimated as having less than 10 faders (0.06 faders/acre) were recorded as zero. A tabular summary of the classification phase follows:

No. frames examined	79
No. 160-acre cells/frame (4 x 38)	152
No. acres/frame (152 x 160)	24,320
Total acres non-type (3332 cells x 160)	533,120
End lap (349 cells x 160)	55,840
Zero count (5073 cells x 160)	811,680
>10 faders (3254 cells x 160)	520,640
Total acres examined (12,008 cells x 160)	1,921,280

5. Scanning the OB imagery to eliminate the obvious non-countable cells.



6 Using a 9x magnification, a single 160-acre cell (at nadir) would fill the entire screen. With increased magnification, only a portion of the cell would be viewed at a time.

OPTICAL-BAR, EQUAL AREA, INTREPRETATION RECORD

FOREST GALLATIN FRAME 111 DATE 2/28/79
INTERPRETER DDB P.I. METHOD MFV NO 1 OF 1

ROW	1	REMARKS	2	REMARKS	3	REMARKS	4	REMARKS
1	20		0		0		0	
2	0		0		0		0	
3	0		0		0		0	
4	0		0		0		0	
5	0		0		0		0	
6	0		0		50		0	
7	0		0		20		90	
8	0		0		0		90	
9	0		0		0		120	
10	0		0		0		50	
11	0		0		0		0	
12	0		0		0		0	
13	0		0		0		0	
14	0		0		0		0	
15	0		15		0		0	
16	50		0		0		0	
17	400		70		40		50	
18	1300		700		150		0	
19	525		1000		950		425	
20	200		875		500		950	
21	140		500		800		100	
22	200		300		450		500	
23	150		15		300		600	
24	60		300	SOME SBW DEFOLIATION	250		150	
25	150		325		375		425	
26	250		225		350		250	
27	350		125		100		500	
28	200		75		110		225	
29	225		150		25		70	
30	110		100		25		50	
31	20		20		0		150	
32	0		0		0		375	
33	0		0		0		150	
34	0		0		0		150	
35	0		0		0		70	
36	0		0		0		0	
37	0		0		30		0	
38	0		200		0		0	
39								
40								

4. Form used to record fader estimates during classification phase.

6. Photointerpretation team classifying the OB photography by 160-acre cells.

Once this phase was completed, the data was arranged by computer program for photo plot selection by PPS. In addition, individual cell quick estimates were arbitrarily assigned damage intensity classes ranging from 1 to 9 for display in a map-like computer printout (figure 7).

Photo Interpretation

The 120, 160-acre photo plots, selected by PPS, were examined with Bausch and Lomb 240 zoom stereomicroscopes (7x to 10x) by three experienced photo interpreters (figure 8). Each photo plot was divided into sixteen 10-acre subplots by a specially produced narrow line (1 mil) grid attached with transparent tape to the back of the frame (figure 9)[7]. Once attached, the equal-area grids on the emulsion side were removed.

All faders within each 10-acre plot were counted and recorded (figure 10). Once this stage was complete, thirty 10-acre subplots were selected by PPS for ground truth. However, only 20 plots were actually visited and cruised because of personnel and time constraints.

Ground Truth

During past photo surveys, ground truth was obtained in late summer or early fall following aerial photography. Since film was not processed and duplicated until September 12, there was insufficient time left to accomplish the preliminary stages and obtain ground truth before the onset of winter. By spring, crowns of the beetle-infested trees possibly could deteriorate to an extent precluding differentiation from the previous year's kill. This concern was unfounded, as the faders retained their foliage through the winter and into early summer (figure 11).

8. Photointerpreter counting faders with the stereomicroscope.

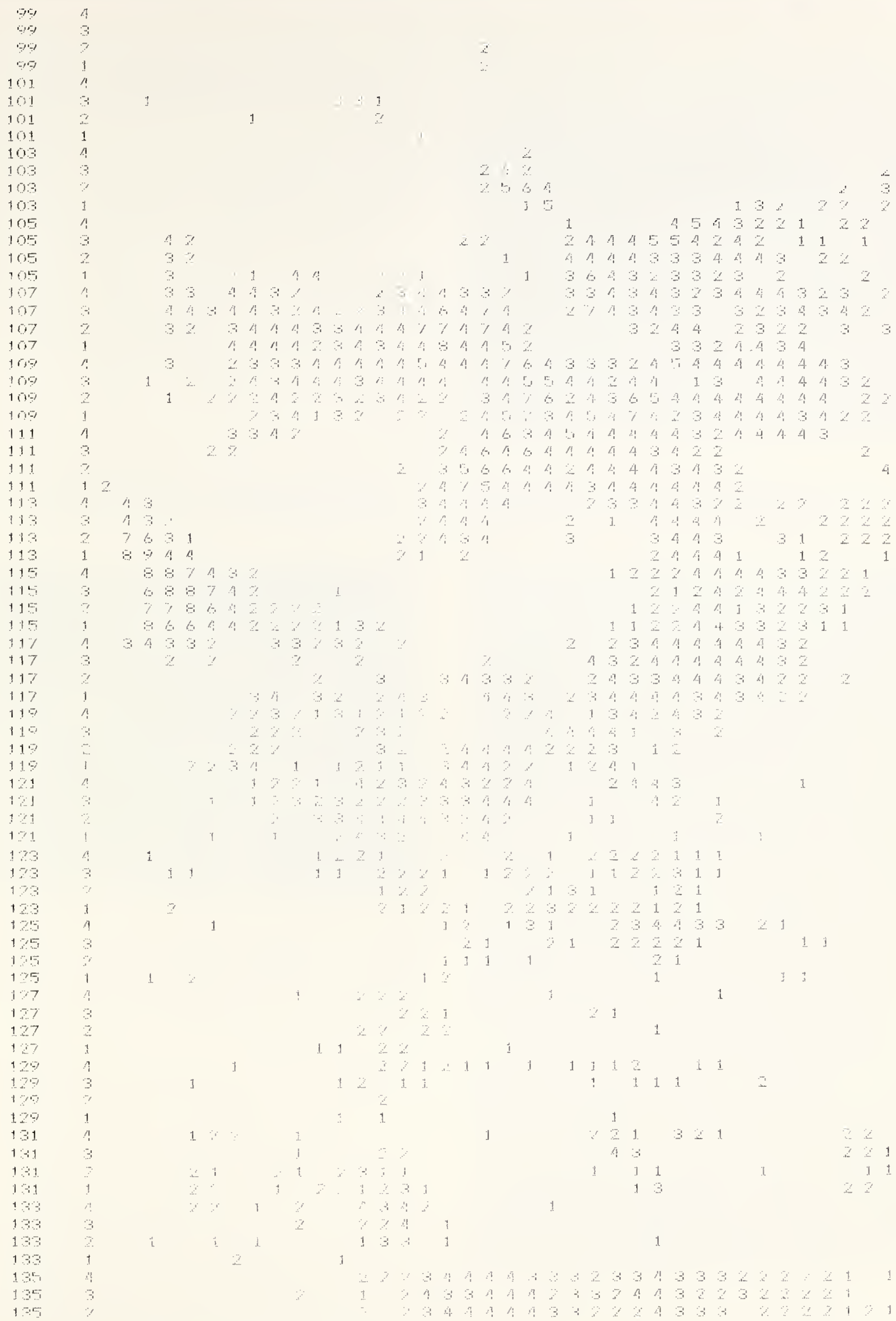
The 10-acre-square plots were located, delineated, and cruised with the aid of a specially constructed stereo viewer (figures 12, 13). Because of personnel and logistical constraints, these steps were done at two different times. A two- or three-person crew[8] would first locate the plot, and using the stereoviewer would locate and mark the plot corners and boundaries with colored plastic flagging. A detailed map giving directions into the plot was then drawn on the back of the recording form (figure 14) to aid the follow-up crew.

Later a three-person follow-up crew consisting of two cruisers and a recorder would string the boundaries and run parallel string lines within the plot at varying intervals for orientation. All faders five inches dbh and larger were blazed[9] and recorded. In some areas the plastic flagging used to designate corners, boundaries, and access to the plot was removed if there was a possibility that it might conflict or be confused with flagging established for other purposes by Forest personnel.

7 Produced by the Forest Service, WO-Geometronics, Rosslyn, VA.

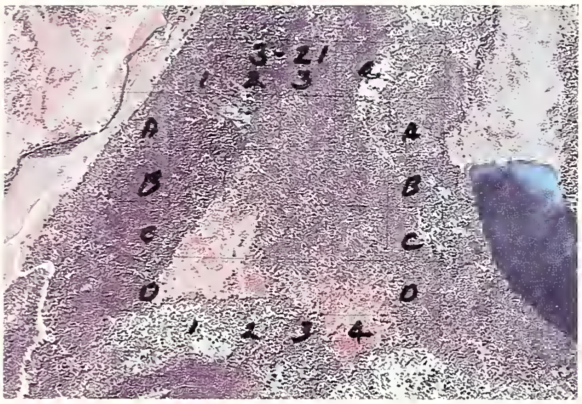
8 At times the number of persons per crew varied, but it was felt that three-person crews were the most efficient.

9 The trees were blazed to eliminate double counting.

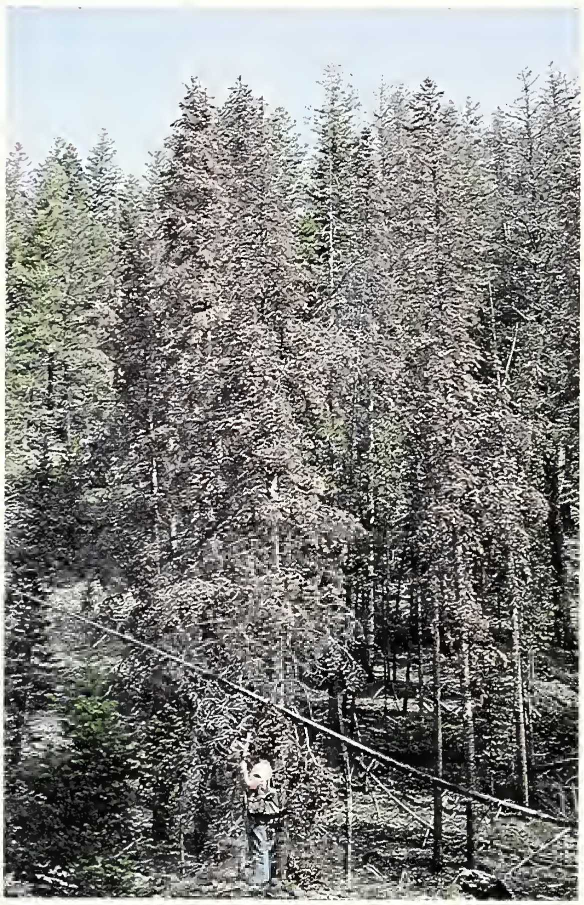


7. *Computer printout showing quick cell classification for 19 alternate OB frames. The classification was arbitrary, ranging from >10 trees (1) to >300 trees (9). Not to scale.*

9. Portion of OB frame near nadir overlaid with 160-acre grid divided into sixteen 10-acre-square plots (35mm Kodachrome enlargement).



11. More or less typical lodgepole faders on ground truth plot No. 109-2-33(B3). These trees were attacked and killed by the mountain pine beetle in 1977 and attained optimum fading in July 1978. Photo (35mm Kodachrome) taken May 27, 1979.



10. Form used to record faders by 10-acre plot.

12. Portable stereoscope used for viewing OB transparencies on the ground plots. Most of the detailed work was done with a specially developed flat field, color-corrected 7x stereoscope.

Plot No. 115-2-4

Beaverhead-Gallatin Optical Bar Photo Interpretation
Record for 160-acre Plot

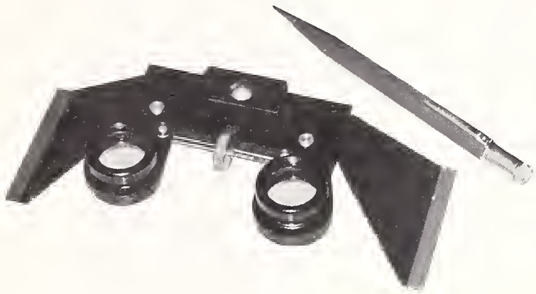
Frame 115 Row 2 Column 4 Interpreter ________
Date 5/16 Magnification 8

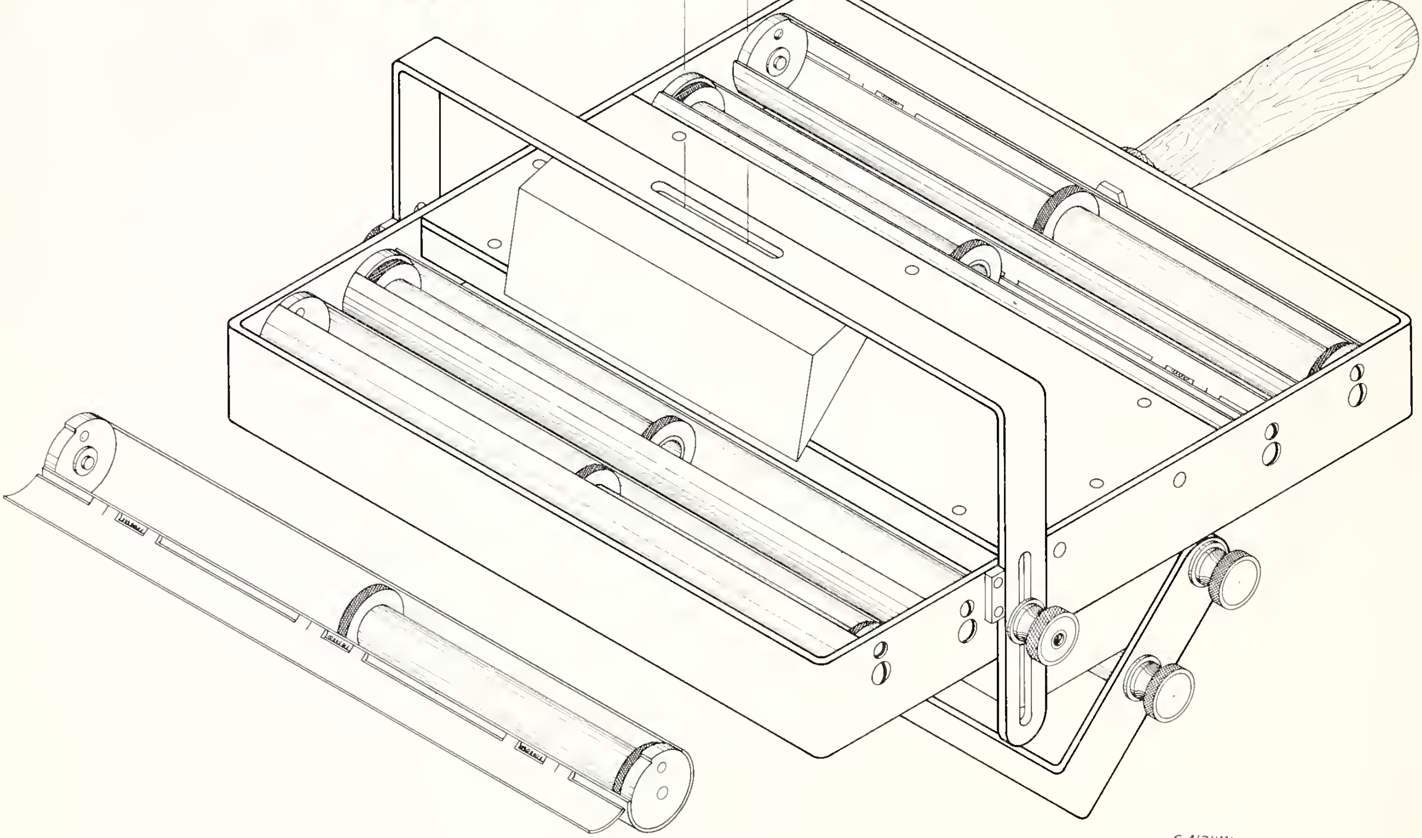
	1	2	3	4	
A	27	198	167	287	A
B	66	147	316	335	B
C	198	133	204	52	C
D	8	55	234	188	D
	1	2	3	4	

N

160-acre plot

Total 2615





13. Drawing showing details of portable stereoscope.
Inset: *7x stereoscope with detachable base.*

14. Ground truth tally form.

Squaw Creek

FIELD TALLY FORM

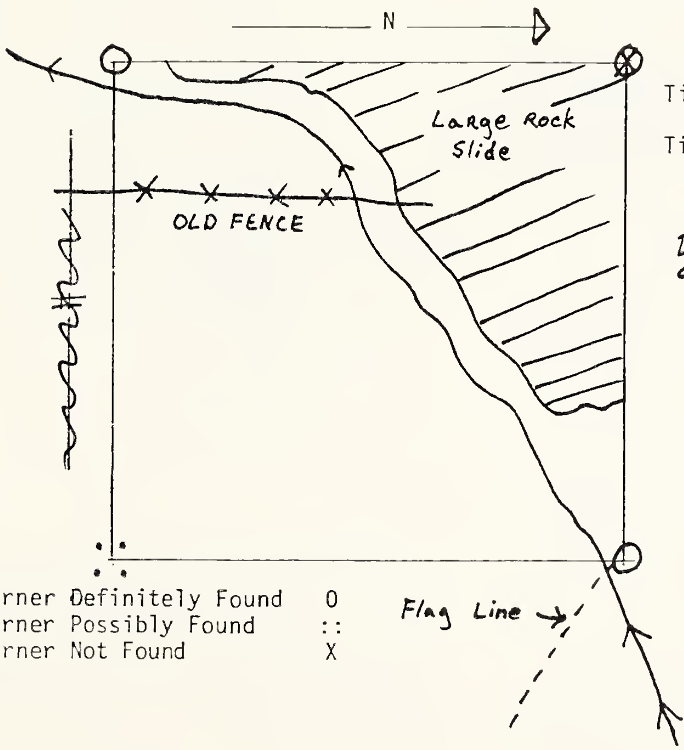
BEAVERHEAD-GALLATIN
OB PHOTOGRAPHY PILOT PROJECT

109-2-33
PLOT B3 CREW MP, NV, AB DATE 8 July 1979

TALLY: :: = 4; ⊓ = 6; ⊠ = 10

1977 ATTACKS (1978 FADERS)

DBH	TOTAL	REMARKS
5	7	
6	21	
7	72	
8	130	
9	130	
10	76	
11	26	
12	12	
13	9	
14	2	
15	2	
16		
TOTAL	487	



Corner Definitely Found 0
Corner Possibly Found ::
Corner Not Found X

REMARKS

Time on Corners 3 1/2 hrs.

Time cruising 3 hrs.

Directions into Plot on back.

Data Analysis

Procedures for estimating the number of faders and total volume combine information from each step in the design. These steps entailed (1) quick cell classification and sample selection of cells, (2) careful photo interpretation of selected cells and sample selection of ground plots, and (3) ground truth collection. Sample selection at each level was based on PPS.

Cell Classification and Sample Selection

Cell classification, based on the quick estimates, resulted in 3254 160-acre cells containing 10 or more faders, or a total of 378,339 faders. The first level sample was selected by a systematic PPS procedure using the following parameters:

Sample size = 120
Total faders estimated = 378,339
Sampling interval = 3153
Random start = 1538

The sampling was done with replacement.

Careful Photo Interpretation and Sample Selection

The selected sample again was photointerpreted. Data was recorded by 10-acre subcells. The next sample was determined based on the ratio of the careful count to the quick count. A systematic PPS sample was done based on the following parameter:

Sample size = 30

$$\text{Total ratio} = \sum_{i=1}^{120} \text{Careful/Quick} = 265.61$$

Sampling interval = 8.85
Random start = 3.55

The 30 cells selected were done with replacement. One 10-acre subcell was selected PPS based on the number of faders counted in each subcell.

Ground Truth Collection

The original intent was to ground sample thirty 10-acre subcells. Personnel restrictions and time constraints limited the actual ground samples to 20. The original sample was used to select 20 from the 30 subcells selected.

Data was analyzed on the assumption that there was a sample of 20 subcells.

Estimation Procedures

$$\hat{Y} = \left\{ \sum_{k=1}^{20} \left[\frac{1}{m} \frac{\sum_{i=1}^{M} Q_i}{Q_i} \right] \cdot \left[\frac{\sum_{i=1}^{m} C_i/Q_i}{C_i/Q_i} \right] \cdot \left[\frac{C_i}{C_{ij}} \right] \cdot X_{ij} \right\} \frac{1}{n}$$

First Stage	Second Stage	Third Stage	Measurement Variable

where: i = 160-acre cell
j = 10-acre subcell
k = ground sample size
Q_i = rapid photo interpretation for cell i; $i = 1, 12{,}008$
$Q = \sum_{i=1}^{M} Q_i$ is the total of all faders counted from the quick interpretation
C_{ij} = the careful interpretation of the jth subcell (10-acre cell) from the ith selected subcell (160-acre cell). $i = 1, m; j = 1, 16$
$C_i = \sum_{i=1}^{16} C_{ij}$ is the total of all faders from careful interpretation from the ith selected cell.
X_{ij} = ground measurement variable (trees or volume) from the jth selected subcell and ith cell.
M = total number of cells = 12,008
m = number of first stage cells selected = 120
Q = 378,339
n = number of ground subcells selected = 20

This formula shows the three levels of sampling. The variables with single subscripts (i), Q_i and C_i take on the cell value for a given subcell (j). Similarly, X_{ij} is the number of trees (or volume) in the ground subcell (j) from selected cell (i).

For computational ease, the formula can be reduced to:

$$\text{let } Q = \sum_{i=1}^{m} Q_i,$$

$$R = \sum_{i=1}^{m} \frac{C_i}{Q_i} \qquad \text{then}$$

$$\hat{Y} = \left[\frac{QR}{m}\right]\left[\sum_{k=1}^{n} \frac{X_{ij}}{C_{ij}}\right] / n$$

The corresponding standard error (SE) is:

$$SE = \sqrt{\left[\frac{1}{m} \cdot Q \cdot R\right]^2 \frac{\sum_{k=1}^{n} \frac{X_{ij}^2}{C_{ij}^2} - \frac{\sum_{k=1}^{n}\left[\frac{X_{ij}}{C_{ij}}\right]^2}{n}}{n(n-1)}}$$

$$RSE = \frac{SE}{\hat{Y}} \quad 100, \text{ expressed as a percent}$$

The steps taken to derive individual expansion factors at each stage in the computation of plot faders and volumes are shown in table 1.

RESULTS

Total lodgepole pine mortality during 1977 over that portion of the outbreak covered by the grids on the 79 panoramic frames (520,640 acres) was estimated at 1,891,510 trees and 27,001,000 cubic feet of volume (table 2). Standard errors were 10.3 and 13.6 percent respectively. The multistage survey (Bennett and Bousfield 1980) covered 270,255 acres and reported 1,270,617 trees and 24,237,335 cubic feet of lodgepole pine killed during 1977 by the mountain pine beetle. These data, however, are not comparable because of the difference in area covered by each survey. The OB survey covered almost twice the area (520,640 vs. 270,255 acres) but the "conventional" survey reported a higher volume per acre, indicating that the OB survey included considerably more "light" infestation. The magnitude of losses from the OB survey would have been greater had not the voids between successive frames and sidelap occurred (figure 1).

DISCUSSION

A regression analysis, based on the relationship between photo and ground counts used in previous double sampling and multistage surveys (Wear *et al.* 1966, Klein *et al.* 1979, Hostetler and Young 1979a), would appear to be inappropriate for this type of panoramic photography. The first level of a regression analysis, the coefficient of determination (R^2), is used as a measure of consistency rather than accuracy, and its use is based on the assumption that every tree has an equal probablity of being detected and counted. The probability of detection is unequal, since each panoramic frame has variable scale. For example, a tree at nadir (~scale 1:30,000) has a greater likelihood of being detected than a similar size tree at 38° (~scale 1:38,000). Heller and Wear (1969) found that ground photo accuracy of individual trees increased with scale, and that a scale of 1:31,680 was the threshold for detection of infestations (groups of 4-10 trees per group) smaller than 50 feet in diameter. This probability of detection is even further reduced by the obliquity and apparent color change in the film at increasing distances from nadir. These phenomena were first suspected

Table 1. Expansion factors and calculations for determining numbers of faders and cubic foot volumes for sample plots[1].

Plot no. (cell)	160-acre Quick count PI	First stage sample expansion	160-acre Careful count PI	Ratio Careful to Quick	Second stage sample expansion	10-acre subcell Careful PI count	Third stage sample expansion	10-acre cell ground fader count	10-acre cell volume	Total expansion for sample	Estimated faders (number)	Estimated volume x 10^3 (cu. ft.)
	(10)	(11) = (2) / (3)(10)	(12)	(13) = (12) / (10)	(14) = (4) / (13)	(15)	(16) = (12) / (15)	(17)	(18)	(19) = (11)(14)(16)	(20) = (19)(17)	(21) = (19)(18)
1	475	6.638	1,055	2.22	119.64	251	4.20	511	4,981	3,335.52	1,704,451	16,614
2	60	52.547	1,449	24.15	11.00	222	6.53	634	6,576	3,774.45	2,393,001	24,821
3	60	52.547	1,449	24.15	11.00	217	6.68	678	12,826	3,861.15	2,617,860	49,523
4	150	21.019	470	3.13	84.86	58	8.10	76	773	14,447.75	1,098,029	11,168
5	2,000	1.576	3,572	1.79	148.39	252	14.17	372	5,376	3,313.83	1,232,745	17,815
6	150	21.019	936	6.24	42.57	124	7.55	586	11,036	6,755.58	3,958,770	74,555
7	75	42.038	1,818	24.24	10.96	248	7.33	655	6,696	3,377.20	2,212,066	22,614
8	75	42.038	1,818	24.24	10.96	290	6.27	837	7,396	2,888.82	2,417,942	21,366
9	450	7.006	867	1.93	137.62	217	4.00	487	5,051	3,856.66	1,878,193	19,480
10	500	6.306	1,786	3.57	74.40	240	7.44	363	4,053	3,490.60	1,267,088	14,147
11	100	31.528	1,042	10.42	25.49	145	7.19	451	5,455	5,778.23	2,605,982	31,520
12	1,600	1.971	2,615	1.63	162.95	133	19.66	490	3,191	6,314.29	3,094,002	20,149
13	200	15.764	1,118	5.59	47.52	90	12.42	107	1,515	9,303.89	995,516	14,095
14	100	31.528	244	2.44	108.86	5	48.80	3	147	167,488.34	502,465	24,621
15	50	63.057	678	13.56	19.59	60	11.30	123	1,174	13,958.74	1,716,925	16,388
16	50	63.057	678	13.56	19.59	86	7.88	84	2,155	9,734.06	817,661	20,977
17	225	14.013	1,843	8.19	32.43	75	24.57	201	2,702	11,165.63	2,244,292	30,170
18	450	7.006	659	1.46	181.92	82	8.04	213	6,024	10,247.23	2,182,660	61,729
19	600	5.255	1,454	2.42	109.76	133	10.93	116	3,115	6,304.30	731,299	19,638
20	550	5.732	726	1.32	201.22	71	10.23	183	2,427	11,799.21	2,159,256	28,637

1 (2) Total faders counted in Quick Count (Q) = 378,339
(3) First stage sample size (m) = 120
(4) Sum of ratio of careful counts to Quick count (R) = 265.61
Ground sample size (n) = 20

during the photointerpretation stage and later empirically confirmed during the ground checks (all three photointerpreters participated in the ground checks).

An analysis was made to determine whether there was a change in detection accuracy with distances from nadir. Since the survey was not designed with this objective in mind, the analysis was more after the fact. The twenty 10-acre ground truth plots were separated into two 10-plot groups, the first 10 falling between nadir and ± 19° and the second 10 falling between ± 20 and 40° (figure 15). The ratio of the ground count to the photo count was computed for each plot, arranged into its respective group, summed, and a mean difference computed. The mean difference of the ground /photo ratios were then subjected to a "T" test. The difference, 3.67 with 18 d.f., was highly significant at the 99 percent level, indicating that the mean ratios were from two different populations. Lacking a more sensitive analysis, it can be assumed that the photo counts were more accurate within ± 20° than those beyond ± 20°.

Two important characteristics intrinsic to OB photography, in addition to variable scale, are obliquity and color.

Obliquity may be as important as variable scale in affecting interpretation accuracy and the final survey results. The angle that an individual vertically standing tree is imaged on the film is equal to the scan angle, i.e. a tree imaged at the 30° point on the film is tilted 30° from vertical—away from nadir. In this situation, faders in a closed or multistoried stand and those on an adverse slope would be either totally or wholly masked by their neighbors. Small openings and occasional breaks in the stand used by ground crews for orientation cannot be seen. Codominant, intermediate, and smaller trees become invisible in some situations.

A significant color shift from nadir outward occurs. Faded trees at or near nadir generally appear yellow to yellow-orange, but become less vivid, and in some instances change to tones of grey, with increasing angle. Mountain pine beetle-faded lodgepole pine possibly could have become confused with Douglas-fir defoliated by the western spruce budworm (*Choristoneura occidentalis* Freeman) in some areas. However, this color attenuation did not occur in a few locations where faded lodgepoles were open grown or on the nadir side of stands bordering open areas. Within the stands, however, faded trees appeared considerably less distinct. This phenomenon is probably due to the relative position of the tree in relation to its immediate surroundings, such as a highly reflective meadow versus a closed stand, and to its orientation and distance from the camera in relationship to the sun.

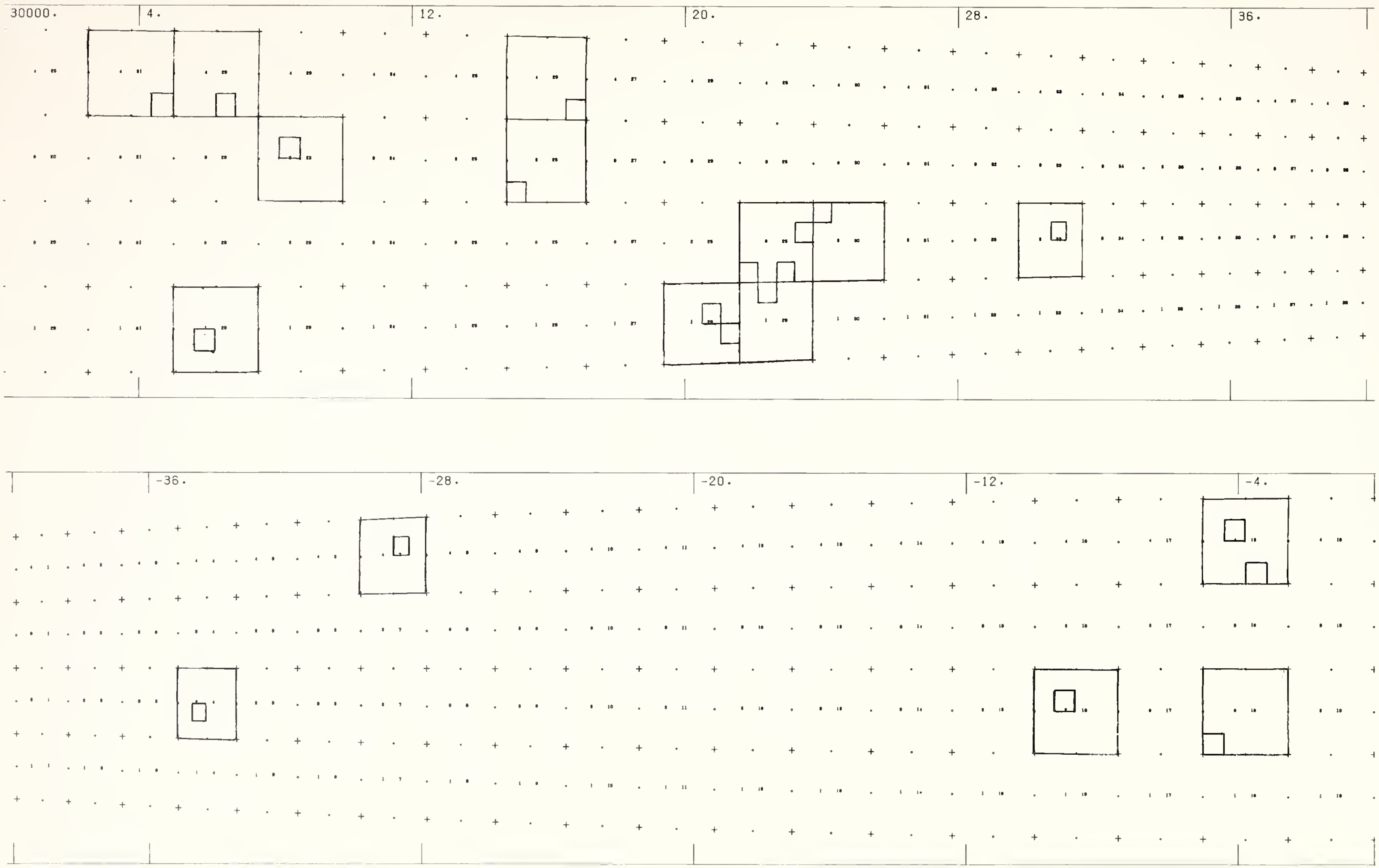
Data gaps created within and between flight lines and topographic distortion prevented production of an accurate infestation map. The flight was planned so that successive frames on parallel flight lines would overlap at the 40° point[10], or approximately 8.5 nm (9.8 miles) from nadir. However, the aircraft strayed off course on the center flight line (figure 1) resulting in more than sufficient sidelap to the west, but a significant holiday to the east. Unfortunately, some of this omitted area contained heavy beetle damage. Holidays, resulting from insufficient (1) overlap and (2) intrack coverage by the equal-area grids also occurred between alternate frames. The overlap at nadir was 50 percent, which also occurred in a previous study (Klein *et al.* 1979). The master equal-area grid covered only two miles of the approximate 2.6-mile intrack distance with

10 This assumed mean datum at 5000 feet and aircraft at 65,000 feet.

Table 2. Estimates of numbers of trees and volume of lodgepole pine killed by the mountain pine beetle in the Beaverhead and Gallatin National Forests, 1977.

	Number of Trees		Percent	Volume (M cu. ft.)			Percent
Acres[1]	total	S.E.	S.E.	per tree[2]	total	S.E.	S.E.
520,640	1,891,510	194,804	10.3	0.0143	27,001	3682	13.6

1. Includes all 160-acre cells which contained 10 or more faders
2. Derived by dividing Volume/Trees



15. Locations of the twenty 10-acre ground plots and their respective 160-acre photo plots in reference to their locations on an optical bar frame. The 20 ground plots fell on 12 different frames.

insufficient overlap preventing complete stereo coverage of some of the photo plots. The grid coverage problem could have been partially resolved by attaching grids to successive frames rather than to alternate ones, but due to the intrinsic elevational distortions, they still would not have matched. An attempt to match or separate individual 160-acre cells in this region would do little to improve the overall accuracy. The same problem would be encountered in the endlap regions where some cells would be partially or totally duplicated. Errors resulting from aircraft attitude, variations in elevation, and frame alignment compounded these alignment problems. Some frames, particularly those in the north half of the middle flight line, were skewed or not aligned perpendicular to the line of flight. This probably resulted from crosswinds (crab) or improper ground speed[11].

The equal-area grid is an extremely useful aid for the transfer of information from photo to map and for establishing a systematic sampling system. In flat or even moderately rolling terrain some position accuracy can be sacrificed, but in mountainous terrain where elevations within a particular frame could vary as much as 5000 feet and where full coverage and a relative accurate data base is needed, map-registered grids should be used when possible. These grids compensate for aircraft altitude and displacement errors induced by elevation. They generally are accurate to within ± 200 feet but are considerably more expensive to produce than the equal-area grids ($47 vs. $1.50). However, it is believed this cost can be reduced by approximately 50 percent with only a slight loss in accuracy by using photogrammetric bridging.[12].

The ground phase of the survey went surprisingly well. Most of the difficulty in locating plot corners and boundaries were in homogenous one-story stands that occurred near the outer edges of the panoramic frames. Of the corners sought, 85 percent were found, 8 percent were judged as "possibly" found and 7 percent were not found. These corners were located by intersection of boundary lines. The stereoviewer worked under all lighting conditions, even in the rain.

The cost of the OB flight was $25,000, but this also included panoramic photography of other mountain pine beetle infestations in portions of the Lewis and Clark and Flathead National Forests and Glacier National Park. The cost of the U-2 aircraft fitted with the KA80A camera was $3750 per flight hour[13]. If the Beaverhead-Gallatin survey had been flown as a single mission, the cost of the photography was estimated to have been $16,376. This included 1080 feet of film, one duplicate, processing, ferry time to and from the project site, and photography time over the area. The roundtrip distance from Moffett Field, California, to Bozeman, Montana, is approximately 1680 miles.

11 The KA80A OB camera is calibrated to operated at constant speed, synchronized with a ground speed of 400 nm (460 miles) per hour. Both systems operate independently. If aircraft speed is less or greater than 400 nm/hour, skewness will result.

12 Liston, *op cit.*

13 R. Ekstrand, Airborne Missions and Applications Division, NASA Ames Research Center, Moffett Field, CA. Personal communication.

CONCLUSION

Number of lodgepole pines and volume killed by the mountain pine beetle can be effectively measured by use of OB photography. Past methods have required two separate and relatively time consuming steps, sketchmapping[14] and aerial photography. In effect, both of these information levels were obtained in less than an hour by a U-2 aircraft. The initial classification phase, comparable to stratification by sketchmapping, took 4-6 persons two weeks to complete, while the actual sketchmap flight was completed in less than four days. Other times are not readily comparable, because the large-scale photography was delayed until October 1978 by contract and weather problems. The OB survey would have been more efficient and resulted in a more reliable map product had there been more accurate aircraft navigation, greater overlap between flight lines and successive frames, faster film processing, and use of a map-registered grid system.

A major concern of all prospective users of NASA-obtained aerial reconnaissance photography is its dependability and future availability. If we and other investigators continue to explore its potential in forest insect and disease detection and develop it to a point where it could become operational, will it be available when and where we need it? Also, if the use of OB and other types of high altitude reconnaissance photography by the Forest Service and other natural resource agencies increases, will NASA be able to meet the demand? Problems relating to excessive turn around time (this survey) and failure to complete the photography of a bark beetle outbreak in Colorado within the optimum time span have already occurred (Dillman *et al.* 1980). At this time, private aircraft with high altitude capabilities are not available and probably won't be for at least another decade.

14 Sketchmapping is a routine function and still would be required for other forest pests not visible on the OB photography.

RECOMMENDATIONS

In the planning and execution of future OB surveys for measuring annual lodgepole pine mortality caused by the mountain pine beetle, the following additions or changes are suggested:

1. The effective working angle of an OB frame should not exceed ± 40° from nadir. The findings of this survey indicate that tree count accuracy improves as one approaches nadir, but the maximum angle at which acceptable accuracy occurs is unknown. Future surveys for lodgepole pine should be designed to establish this threshold.
2. Flight lines should be no further than 15 nm (17 miles) apart. This will permit some deviation from the planned flight line and still permit sufficient endlap at the ± 40° point.
3. Photographic requirements to NASA should specify a minuimum of 55 percent forward lap (nadir) at mean datum. In this survey portions of several photo plots, particularly those that fell near nadir, were not in stereo. Fortunately, none of prospective ground plots that fell in these areas were selected for ground truth!
4. If a relatively accurate map product is desired, photo to map transfers should be made with map-registered grids. A photographic bridging technique should be attempted, although some accuracy may be sacrified.
5. Inexpensive monoscopic projection equipment for simultaneous viewing of larger areas (at least 640 acres) with at least 8x magnification should be developed.
6. The ideal crew size for ground truth data collection is three, with one person recording and the other two detecting and measuring the affected trees. The use of visible string lines is mandatory for definitive boundary separation and crew orientation.
7. The turnaround time between photography, processing, and delivery to the user should not exceed 10 days.
8. The 10-acre-square ground plot is satisfactory. The size and the number of trees found on a plot does not seem to be as time-

consuming as originally thought. More time is spent traveling to the plot, locating it, and establishing its boundaries than cruising. Of the total plot time, 52 percent was spent on corner and boundary location while 48 percent was spent cruising.

REFERENCES

Bennett, D.D. and W.E. Bousfield. 1980. A pilot survey to measure annual mortality of lodgepole pine caused by the mountain pine beetle on the Beaverhead and Gallatin National Forests (in preparation).

Dillman, R.D., S.S. Chu, and J.C. Prill. 1980. A procedures verification test in Colorado (Stage III final report). USDA For. Serv., Nationwide Forestry Applications Program, Houston, TX (in preparation).

Duggan, I.E., B.E. Edwards, R.F. Liston, and A.R. Stage. 1977. Western dead timber pilot study (Phase II). Final Report, USDA For. Serv., Nationwide Forestry Applications Program, Houston, TX.

Heller, R.C. and J.F. Wear. 1969. Sampling forest insect epidemics with color films. Proc. Sixth International Symposium on Remote Sensing of the Environment, Institute of Science and Technology, Univ. of Mich.

Hostetler, B.B. and R.W. Young. 1979a. A pilot survey to measure annual mortality of ponderosa pine caused by the mountain pine beetle in the Black Hills of South Dakota and Wyoming. USDA For. Serv. Tech. Rep. R2-15. Rocky Mtn. Region, Lakewood, CO.

Hostetler, B.B. and R.W. Young. 1979b. Estimation procedures for determining annual tree mortality caused by the mountain pine beetle. USDA For. Serv. Tech. Rep. R2-20. Rocky Mtn. Region, Lakewood, CO.

Klein, W.H., W. Bailey, E. Wilson, and I.E. Duggan. 1978. Efficiency of two high elevation camera systems for assessment of insect-caused tree mortality. USDA For. Serv., FI&DM/MAG, Rep. 78-3. Davis, CA.

Klein, W.H., D.D. Bennett, and R.W. Young. 1979. A pilot survey to measure annual mortality of lodgepole pine caused by the mountain pine beetle. USDA For. Serv., FI&DM-/MAG and Intermtn. Region, MAG Rep. 78-4, Davis, CA.

McGregor, M.D., D.D. Bennett, and H.E. Meyer. 1978. Evaluation of mountain pine beetle infestations, Hebgen Lake Ranger District, Gallatin National Forest, Montana. USDA For. Serv., Northern Region, Rep. 79-6. Missoula, MT.

Wear, J.F., R.B. Pope, and P.W. Orr. 1966. Aerial photographic techniques for estimating damage by insects in western forests. USDA For. Serv., Pacific NW For. and Range Exp. Sta., Portland, OR.